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Yao, Zhilei; Xiao, Lan; Guerrero, Josep M.

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# An Improved Control Strategy for the Three-Phase Grid-Connected Inverter

Zhilei Yao<sup>1</sup>, Lan Xiao<sup>2</sup>, and Josep M. Guerrero<sup>3</sup>

1. School of Electrical Engineering, Yancheng Institute of Technology, Yancheng Jiangsu 224051, P. R. China;

2. Jiangsu Key Laboratory of New Energy Generation and Power Conversion, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, P. R. China;

3. Department of Energy Technology, Aalborg University, Aalborg 9220, Denmark.

E-mail: nhyzl@163.com

*Abstract*—An improved control strategy for the three-phase grid-connected inverter with space vector pulse width modulation (SVPWM) is proposed. When the grid current contains harmonics, the d- and q-axis grid currents will be interacted, and then the waveform quality of the grid current will be poorer. As the reference output voltage cannot directly reflect the change of the reference grid current, the dynamic response of the grid-connected inverter is slow. In order to solve the aforementioned problems, the d- and q-axis grid currents in the decoupled components of the grid current controller can be substituted by the d- and q-axis reference grid currents, respectively. The operating principles of the traditional and proposed control methods are illustrated. Experimental results for a 15-kVA three-phase grid-connected inverter with SVPWM verify the theoretical analysis. Compared with the traditional control strategy, the grid-connected inverter with the improved control strategy has high waveform quality of the grid current, small ripple power, and fast dynamic response.

*Index Terms*—Inverters; LCL filter; grid-connected; SVPWM; total harmonic distortion.

## I. INTRODUCTION

The increasing concern about the environmental pollution and fossil energy shortage has given a high impetus to the use of renewable energy sources, such as solar energy, fuel cells, and wind energy, which are clean, pollution-free, and renewable. The output of solar cells and fuel cells is dc voltage, and the output of wind turbines is ac voltage with variable frequency, but the grid is ac voltage with constant frequency. Therefore, the grid-connected inverters play an important part in the distributed generation systems [1]–[9].

As the LCL-filter-based three-phase grid-connected inverters with space vector pulse width modulation (SVPWM) have high input-voltage utilization rate, low total harmonic distortion (THD) of the grid current, zero steady-state error, and decoupled d-q current control loops, they are widely used in medium and high power applications [10]–[16]. However, the traditional decoupled control method (shown in Fig. 1) is realized by adding the minus q-axis grid current and the positive d-axis grid current



3) The input voltage ( $U_{in}$ ) is larger than the peak value of the grid line voltage.

4) The d- and q-axis reference output voltages ( $u_d^*$  and  $u_q^*$ ) are equal to the d- and q-axis output voltages ( $u_d$  and  $u_q$ ) at steady state, respectively.

5) The d- and q-axis reference grid currents ( $i_{gd}^*$  and  $i_{gq}^*$ ) are constant DC values at steady state.

As the filter capacitor  $C_f$  can be neglected at low frequency, the LCL filter can be equivalent to the L filter at low frequency [18]. Thus, the voltages  $u_d$  and  $u_q$  can be obtained [19].

$$u_d = L \frac{di_{gd}}{dt} + u_{gd} - \omega L i_{gq} \quad (1)$$

$$u_q = L \frac{di_{gq}}{dt} + u_{gq} + \omega L i_{gd} \quad (2)$$

where  $\omega$  is the grid angular frequency and  $L = L_1 + L_2$ .

From (1) and (2), the decoupled control method can be realized by adding  $-\omega L i_{gq}$  and  $\omega L i_{gd}$  into the output of the d- and q-axis PI regulators ( $\Delta u_d$  and  $\Delta u_q$ ), respectively, as shown in Fig. 2. Therefore, the voltages  $u_d^*$  and  $u_q^*$  can be obtained as

$$u_d^* = \Delta u_d + u_{gd} - \omega L i_{gq} \quad (3)$$

$$u_q^* = \Delta u_q + u_{gq} + \omega L i_{gd} \quad (4)$$

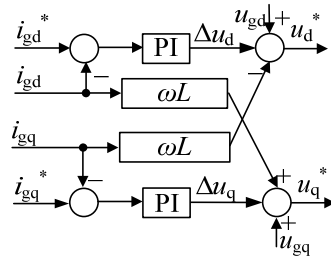


Fig. 2. Principle block diagram of the traditional control method.

### A. Dynamic Response

As the decoupled components  $-\omega L i_{gq}$  and  $\omega L i_{gd}$  cannot directly reflect the change of  $i_{gq}^*$  and  $i_{gd}^*$  from Fig. 2, respectively, the dynamic response is slow.

### B. Waveform Quality of the Grid Current

When the grid current contains harmonics at steady state, the currents  $i_{gd}$  and  $i_{gq}$  will have ripple, which can be estimated as

$$i_{gd} = i_{gd}^* + \tilde{i}_{gd} \quad (5)$$

$$i_{gq} = i_{gq}^* + \tilde{i}_{gq} \quad (6)$$

where  $\tilde{i}_{gd}$  and  $\tilde{i}_{gq}$  are the ripples of  $i_{gd}$  and  $i_{gq}$  at steady state, respectively.

Therefore, (7) and (8) can be gained by substituting (6) and (5) into (3) and (4), respectively.

$$u_d^* = \Delta u_d + u_{gd} - \omega L i_{gq}^* - \omega L \tilde{i}_{gq} \quad (7)$$

$$u_q^* = \Delta u_q + u_{gq} + \omega L i_{gd}^* + \omega L \tilde{i}_{gd} . \quad (8)$$

As the voltages  $u_d^*$  and  $u_q^*$  contain  $\tilde{i}_{gq}$  and  $\tilde{i}_{gd}$  from (7) and (8), respectively, the currents  $\tilde{i}_{gd}$  and  $\tilde{i}_{gq}$  interact, which will worsen the waveform quality of the grid current from Fig. 2.

### III. PROPOSED CONTROL METHOD

In order to improve the waveform quality of the grid current and the dynamic response of the grid-connected inverter, the currents  $i_{gd}^*$  and  $i_{gq}^*$  are used in the decoupled components of the grid current controller to replace  $i_{gd}$  and  $i_{gq}$ , respectively, as shown in Fig. 3. From Fig. 3, the voltages  $u_d^*$  and  $u_q^*$  can be gained as

$$u_d^* = \Delta u_d + u_{gd} - \omega L i_{gq}^* \quad (9)$$

$$u_q^* = \Delta u_q + u_{gq} + \omega L i_{gd}^* . \quad (10)$$

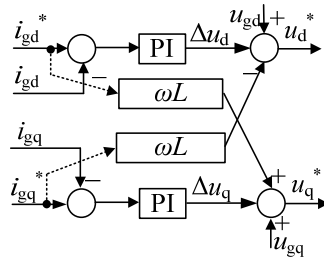


Fig. 3. Principle block diagram of the proposed control method.

#### A. Dynamic Response

As the decoupled components  $-\omega L i_{gq}^*$  and  $\omega L i_{gd}^*$  can directly reflect  $i_{gq}^*$  and  $i_{gd}^*$  from Fig. 3, the dynamic response can be improved compared with the traditional control strategy.

#### B. Waveform Quality of the Grid Current

Compared with the proposed control strategy, the added ripples of  $u_d^*$  and  $u_q^*$  ( $\tilde{u}_d^*$  and  $\tilde{u}_q^*$ ) in the traditional control method can be obtained by (7) and (8) subtracting (9) and (10), respectively.

$$\tilde{u}_d^* = -\omega L \tilde{i}_{gq} \quad (11)$$

$$\tilde{u}_q^* = \omega L \tilde{i}_{gd} . \quad (12)$$

The voltages  $u_d^*$  and  $u_q^*$  in the proposed control strategy have smaller ripples than that in the traditional control strategy from

(11) and (12), respectively, so  $\tilde{i}_{gd}$  and  $\tilde{i}_{gq}$  can be reduced, and then the waveform quality of the grid current can be improved with the proposed control method.

Assuming that the three-phase voltages are pure sine waves and balanced, the voltage  $u_{gd}$  is equal to zero. Therefore, the instantaneous active and reactive powers ( $p$  and  $q$ ) can be deduced [20].

$$p = \frac{3}{2} u_{gd} i_{gd} \quad (13)$$

$$q = -\frac{3}{2} u_{gd} i_{gq} \quad (14)$$

Therefore, the ripples of  $p$  and  $q$  ( $\tilde{p}$  and  $\tilde{q}$ ) in the traditional control method are larger than that in the proposed control method from the aforementioned analysis, (13) and (14), respectively.

As  $\tilde{i}_{gd}$  and  $\tilde{i}_{gq}$  are often low, the currents  $i_{gd}$  and  $i_{gq}$  can approximate to constant dc currents. Thus, the derivatives of  $i_{gd}$  and  $i_{gq}$  are equal to zero, and then  $u_d^*$  and  $u_q^*$  can be estimated from assumption 4),  $u_{gq} = 0$ , (1), (2), (13), and (14).

$$u_d^* = u_{gd} + \frac{2\omega Lq}{3u_{gd}} \quad (15)$$

$$u_q^* = \frac{2\omega Lp}{3u_{gd}} \quad (16)$$

When  $u_{gd}$  is constant, the voltage  $u_d^*$  equals to  $u_{gd}$  plus a proportion of  $q$ , while  $u_q^*$  is proportional to  $p$ .

#### IV. EXPERIMENTAL RESULTS

A 15-kVA three-phase SVPWM grid-connected inverter has been constructed to verify the theoretical analysis with the following parameters:

- 1) the input voltage ( $U_{in}$ ): 700 V;
- 2) the grid phase voltage ( $u_g$ ): 240 V/50 Hz;
- 3) the inverter-side filter inductor ( $L_1$ ): 1.8 mH;
- 4) the grid-side filter inductor ( $L_2$ ): 1.5 mH;
- 5) the filter capacitor ( $C_f$ ): 20  $\mu$ F;
- 6) the switching frequency ( $f_s$ ): 5 kHz;
- 7) the proportional coefficient of the current regulator ( $K_p$ ): 1;
- 8) the integral coefficient of the current regulator ( $K_I$ ): 1000.

The selection of filter parameters and current regulator constants can be referred to [21].

Fig. 4 presents the waveforms of the step response under different type of powers. The ripples of  $u_d^*$  and  $u_q^*$  with the traditional

control method are larger than that with the proposed control method, which causes that the ripples of  $p$  and  $q$  with the traditional control method is also larger than that with the proposed control method. Therefore, experimental results verify the theoretical analysis.

Fig. 5 shows the waveforms of the step-up response under different type of powers.

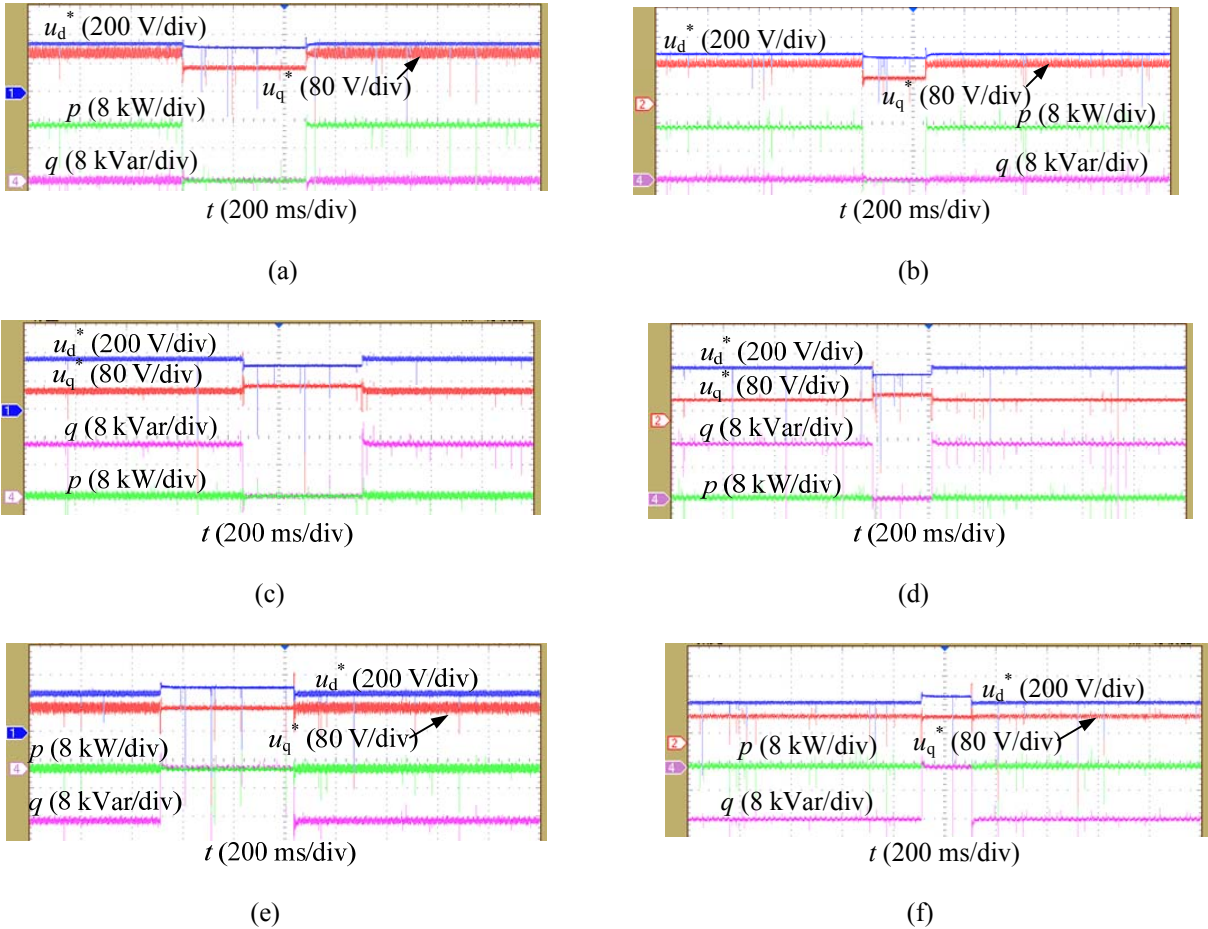
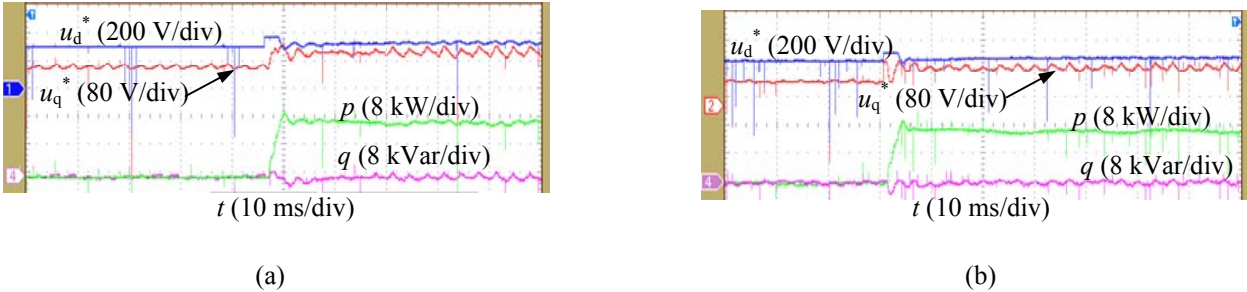


Fig. 4. Waveforms of the step response under different type of powers. (a) Active power in the traditional control method. (b) Active power in the proposed control method. (c) Inductive reactive power in the traditional control method. (d) Inductive reactive power in the proposed control method. (e) Capacitive reactive power in the traditional control method. (f) Capacitive reactive power in the proposed control method.



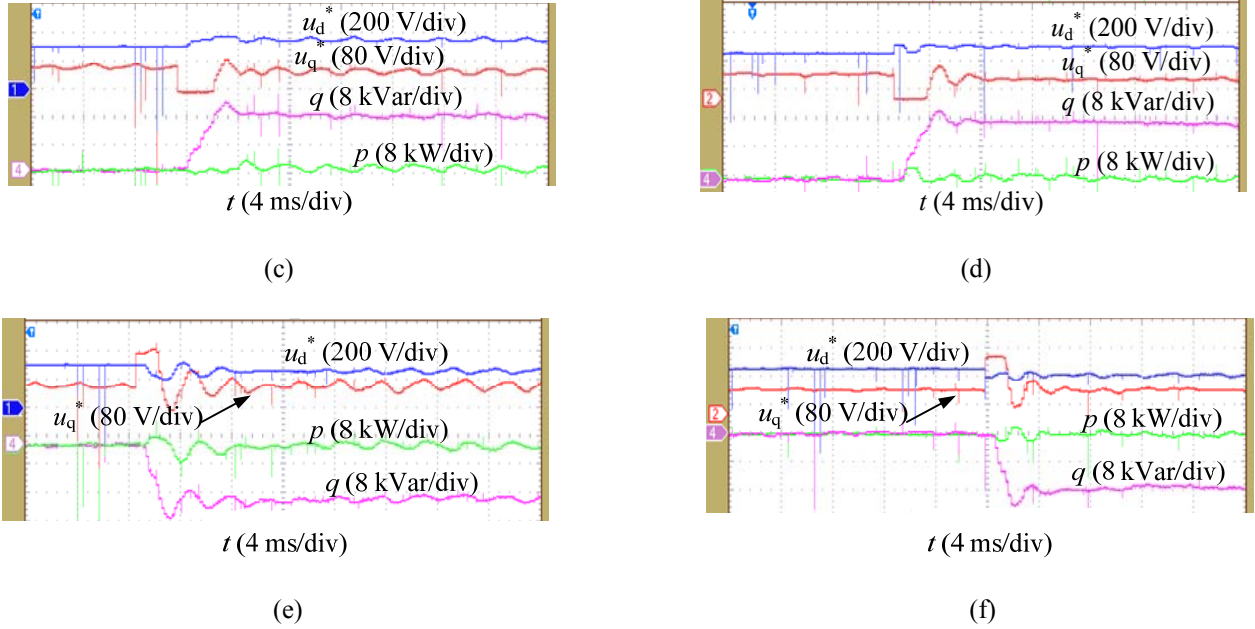


Fig. 5. Waveforms of the step-up response under different type of powers. (a) Active power in the traditional control method. (b) Active power in the proposed control method. (c) Inductive reactive power in the traditional control method. (d) Inductive reactive power in the proposed control method. (e) Capacitive reactive power in the traditional control method. (f) Capacitive reactive power in the proposed control method.

#### A. Step-Up Response at Active Power

From (13),  $i_{gd}^*$  should be positive at active power. From Figs. 2 and 3, when  $i_{gd}^*$  changes from zero to the rated value and  $i_{gq}^*$  maintains zero, the voltage  $u_d^*$  becomes positive saturated as  $i_{gd}$  cannot change suddenly at both control methods. In addition, as  $i_{gq}^*$  maintains zero and  $i_{gq}$  cannot be changed suddenly, the voltage  $\Delta u_q$  keeps constant at both control methods. As the q-axis decoupled component is  $\omega L i_{gd}$  in the traditional control strategy, the voltage  $u_q^*$  increases gradually from Fig. 2. However, as the q-axis decoupled component is  $\omega L i_{gd}^*$  in the proposed control strategy, the voltage  $u_q^*$  suddenly changes to the rated value from Fig. 3. Therefore, the step-up response at active power in the proposed control method is faster than that in the traditional control method from Figs. 5(a) and (b).

#### B. Step-Up Response at Inductive reactive power

From (14),  $i_{gq}^*$  should be negative at inductive reactive power. When  $i_{gq}^*$  changes from zero to the rated value and  $i_{gd}^*$  maintains zero, the voltage  $u_q^*$  changes to zero as  $i_{gq}$  cannot change suddenly and the minimum value of  $u_q^*$  is limited to zero at both control methods from Figs. 2 and 3. Moreover, as  $i_{gd}^*$  maintains zero and  $i_{gd}$  cannot be changed suddenly, the voltage  $\Delta u_d$  remains unchanged at both control methods from Figs. 2 and 3. As the d-axis decoupled component is  $-\omega L i_{gq}$  in the traditional control strategy, the voltage  $u_d^*$  increases gradually from Fig. 2. However, as the d-axis decoupled component is  $-\omega L i_{gq}^*$  in the proposed control strategy, the voltage  $u_d^*$  suddenly increases to the rated value from Fig. 3. Therefore, the step-up response at inductive



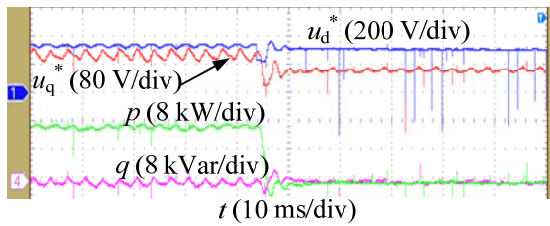
reactive power with the proposed control method is faster than that with the traditional control method from Figs. 5(c) and (d).

### C. Step-Up Response at Capacitive reactive power

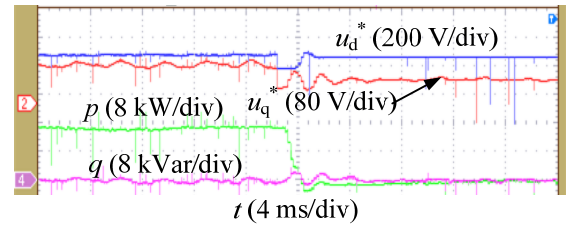
From (14),  $i_{gq}^*$  should be positive at capacitive reactive power. When  $i_{gq}^*$  changes from zero to the rated value and  $i_{gd}^*$  maintains zero, the voltage  $u_q^*$  changes to positive saturated as  $i_{gq}$  cannot change suddenly at both control methods from Figs. 2 and 3. One point that needs to be clarified is that the positive saturated value of  $u_q^*$  is smaller than that of  $u_d^*$  to limit the maximum active power from (15) and (16). The voltage  $\Delta u_d$  is similar as that at the inductive reactive power. As the d-axis decoupled component is  $-\omega L i_{gq}$  in the traditional control strategy, the voltage  $u_d^*$  decreases gradually from Fig. 2. However, as the d-axis decoupled component is  $-\omega L i_{gq}^*$  in the proposed control strategy, the voltage  $u_d^*$  suddenly decreases to the rated value from Fig. 3. Therefore, the step-up response at capacitive reactive power with the proposed control method is faster than that with the traditional control method from Figs. 5(e) and (f).

The waveforms of the step-down response under different type of powers are shown in Fig. 6. Fig. 6 has the similar conclusion as Fig. 5 from Figs. 2 and 3. The difference between Figs. 5 and 6 is that the changes of  $u_d^*$  and  $u_q^*$  are both in the opposite direction.

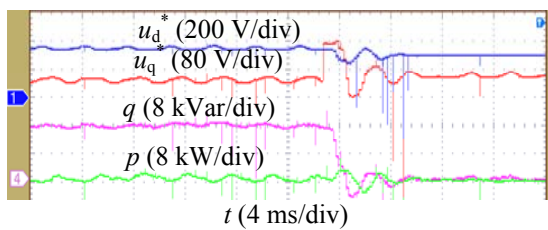
The waveforms of  $u_{ga}$ ,  $i_{ga}$ ,  $i_{gb}$ , and  $i_{gc}$  under different type of powers are given in Fig. 7. From Fig. 7, the waveform quality of the grid current with the proposed control method is better than that with the traditional control method.



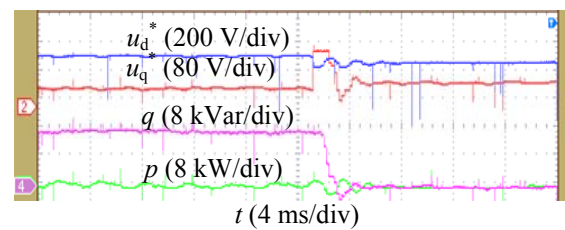
(a)



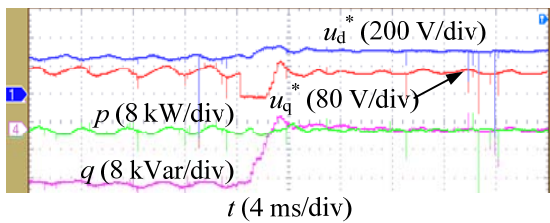
(b)



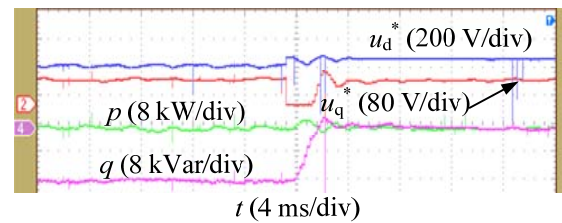
(c)



(d)



(e)



(f)

Fig. 6. Waveforms of the step-down response under different type of powers. (a) Active power in the traditional control method. (b) Active power in the proposed control method. (c) Inductive reactive power in the traditional control method. (d) Inductive reactive power in the proposed control method. (e) Capacitive reactive power in the traditional control method. (f) Capacitive reactive power in the proposed control method.

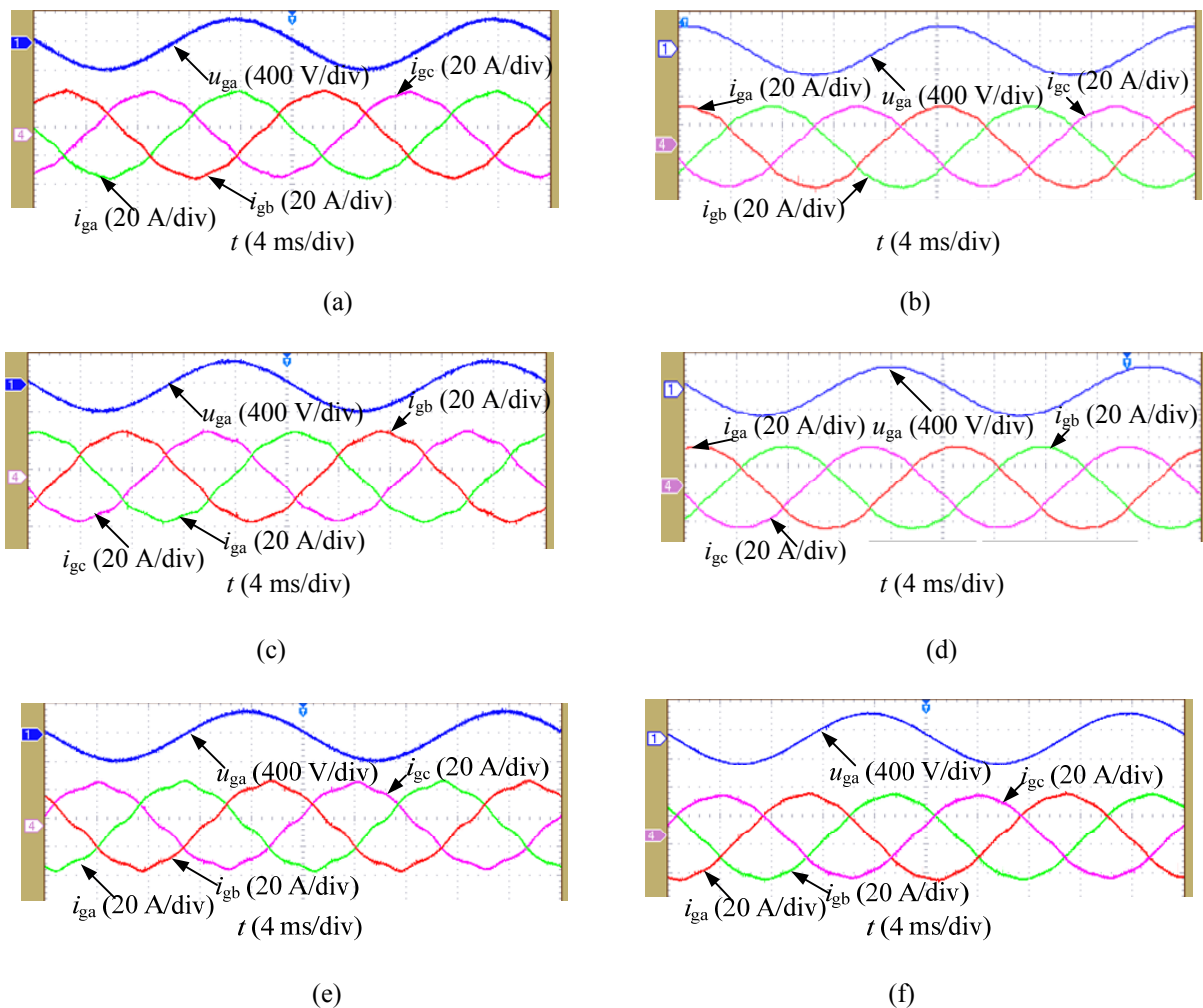


Fig. 7. Waveforms of  $u_{ga}$ ,  $i_{ga}$ ,  $i_{gb}$ , and  $i_{gc}$ . (a) Active power in the traditional control method. (b) Active power in the proposed control method. (c) Inductive reactive power in the traditional control method. (d) Inductive reactive power in the proposed control method. (e) Capacitive reactive power in the traditional control method. (f) Capacitive reactive power in the proposed control method.

The THD of the grid current and dynamic response time are illustrated in Table I. The THD of the grid current with the proposed control method is smaller than that with the traditional control method. Moreover, the dynamic response with the proposed control method is faster than that with the traditional control method.

TABLE I

THE THD OF THE GRID CURRENT AND DYNAMIC RESPONSE TIME

	THD of the grid current			Step-up response time (ms)			Step-down response time (ms)		
	Active power	Inductive reactive power	Capacitive reactive power	Active power	Inductive reactive power	Capacitive reactive power	Active power	Inductive reactive power	Capacitive reactive power
Traditional control method	4.1%	4.6%	6.4%	20	9	15	10	7.5	9
Proposed control method	3.5%	3.1%	2.9%	13	7	6.5	8	5.5	7

## V. CONCLUSIONS

This paper has proposed an improved SVPWM control strategy for the three-phase grid-connected inverter. The reference grid current is used in the decoupled components of the grid current controller in the proposed control method to replace the grid current. Experimental results of a 15-kVA three-phase SVPWM grid-connected inverter show that the grid-connected inverter with the proposed control strategy has high waveform quality of the grid current, small ripple power, and fast dynamic response compared with the traditional control strategy.

## VI. ACKNOWLEDGMENT

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